Abstract — This paper reports different strategies for electrical dispersion compensation of optical single sideband transmission systems. We investigate and compare the mitigation of the chromatic dispersion impairment using dispersive microstrip lines, Butterworth filters, and hybrid schemes employing an adaptive filter. Simulation results are presented at 10 Gbit/s, proving transmission over 600km of dispersive fiber employing feasible stand alone solutions, and without recurring to the use of optical dispersion compensation.

I. INTRODUCTION

The fast growth of data exchange, particularly internet traffic, has led to a dramatic increase in the demand for transmission bandwidth, imposing an immediate requirement for broadband networks. Currently core networks widely employ Wavelength Division Multiplexing (WDM) and Dense WDM (DWDM) to offer high capacity and long reach transmission. Since the majority of the installed optical fiber is Non-Dispersion-Shifted, for high bit rate signals the most critical effect is chromatic dispersion (CD). Two methods have been deployed for mitigation of the effects of CD: the use of specific modulation formats to increase the resilience of the transmitted signal; and compensation of CD by optical, electrical, or both methods.

In Optical Single Sideband (oSSB) signals one of the sidebands is suppressed, which leads to an inherent increase in the channel density on DWDM systems, but also to the minimization of the influence of CD. Furthermore, efficient and low cost electrical dispersion compensation (EDC) is enabled after simple auto-homodyne (direct) detection.

Since it actuates in the same domain where the phenomenon is caused, optical dispersion compensation is a straightforward method; however, the optical techniques tend to be bulky and expensive. In addition, these devices are usually tuned for one wavelength: as a consequence the residual dispersion can be significant in the adjacent channels due to non ideal CD compensation. Therefore EDC is important as a complement for optical dispersion compensation or even to actuate alone, compensating several thousands of ps/nm of accumulated CD in each 10Gbit/s channel.

Electrical dispersion compensation is a widespread technique when used after heterodyne detection of Double Sideband (DSB) signals, where spectral back folding does not occur; common methods to perform EDC of these signals are: microstrip lines, Butterworth filters, and fractionally spaced transversal filters. EDC of homodyne received DSB signals has been developed, however it requires high speed heavy processing at the receiver, or the compensated fiber lengths are reduced. Since no spectral back folding occurs after homodyne detection of optical SSB signals, efficient EDC can be performed at the emitter or receiver side, or both (distributing the EDC strength by two locations); the reported techniques consist on simple microstrip dispersive lines, transversal filters (adaptive or not), Butterworth filters, and a hybrid combination of microstrip lines and adaptive filter.

This paper reports an overview on the use of EDC for direct detected optical SSB signals at 10 Gbit/s at the receiver side, employing the transmitter setup proposed by Sieben. A study of EDC based on a bank of microstrip line sections is presented, performing the compensation of a large range of accumulated chromatic dispersion, suitable for transparent metro networks. The influence of a Butterworth filter placed at the receiver to compensate CD is analyzed. A hybrid EDC scheme based on a microstrip line followed by an adaptive transversal filter is considered, and a novel hybrid configuration is presented: a Butterworth filter followed by the same adaptive transversal filter.

II. GENERATION OF OPTICAL SSB

The configuration utilized in this work was proposed by Sieben et al; it includes a quadrature filter that performs a broad band phase shift of \( -90° \) (Hilbert transform) and a dual arm Mach-Zehnder modulator. This method is appropriate for carrier unsuppressed oSSB generation; is low cost and simple in the optical domain; has low insertion losses; and the back-to-back signal is not distorted by the Hilbert transform signal. The electrical field at the oSSB transmitter output, \( E_{oSSB}(t) \), is given by (1)\(^\text{[1]}\).

\[
E_{oSSB}(t) = e^{j\omega t} \cdot \cos \left( \pi x \cdot m(t) - \frac{\pi}{4} \right) e^{j\pi \tilde{m}(t)}. \tag{1}
\]

Where \( m(t) \) is the data signal \((-0.5 \leq m(t) \leq 0.5)\); \( x \) is a parameter known as modulation depth (in this work \( x = 0.22 \), conferring an extinction ratio (ER) of 7.7 dB); and \( \tilde{m}(t) \) stands for the Hilbert transform of the data signal. In this work the Hilbert transform signal is obtained using the measured transfer function of a commercially available hybrid coupler from Agilent (model 87310B), which features...
-3 dB cut-off frequencies of 1 GHz and 18 GHz.

III. SIMULATION SETUP

The simulation setup utilized for the 10 Gb/s oSSB transmission tests performed throughout this paper is depicted in Fig. 1. A 10 Gb/s de Bruijn binary sequence with $2^{10}$ bits is generated with 32 samples per bit. In the ‘Electrical signaling formatter’ the binary sequence is non-return-to-zero shaped. Optical SSB modulation is performed using the modulator described in section II. The bandwidth of the electrical processing and modulation is simulated by a 3rd order Bessel filter with a -3 dB bandwidth of 7.5 GHz.

In this work linear fiber transmission is considered, since its purpose is to evaluate the penalty arising from chromatic dispersion accumulation and its compensation in the electrical domain. The fiber dispersion parameter ($D$) is $17$ ps/nm/km and the dispersion slope ($S$) $80$ s/m³.

Before detection the signal is optically filtered, to simulate the channel bandwidth. The optical filter is a 2nd order Gaussian filter with -3 dB bandwidth of 30 GHz, centered with the optical carrier. The Positive Intrinsic Negative (PIN) photodiode is modeled by an ideal square law device followed by a 3rd order low pass Bessel filter with 7.5 GHz -3 dB bandwidth. Post compensation is performed by several means, which are described hereafter.

The system performance is evaluated through eye opening penalty (EOP) measurement, defined as:

$$ EOP = -10 \cdot \log \left( \frac{\Delta I_{oSSB}}{\Delta I_{REF}} \right), $$

where $\Delta I_{oSSB}$ is the height of highest rectangle of 20% of the bit period than can be fitted inside the eye diagram of the oSSB signal to be analyzed and $\Delta I_{REF}$ is the height of the window inside the reference signal eye diagram: an unfiltered signal with $7.7$ dB of ER (the same as for the OSSB signals).

From (3) we observe that the dispersion affects the optical signal phase but not its amplitude.

Fig. 2 illustrates the phase dynamics after direct (self homodyne) detection for optical DSB and SSB signals.

Detection of an optical DSB signal results in spectral back folding – the positive and negative spectral sidebands are overlapped, as shown in Fig. 2, therefore the fiber dispersion becomes difficult to compensate in the electrical domain. On the other hand, when an optical SSB signal is detected after the fiber, there is no spectral back folding. This means that all the signal phase information is kept in the electrical detected signal, thus the original phase can be recovered.

From the previous considerations, the chromatic dispersion of direct detected OSSB can be compensated by linear filtering, where the electrical filter transfer function is given by:

$$ H_{EDC}(f) = \exp \left( -j \frac{\pi DL^2}{c} f \text{sign}(f) \right). $$

B. Microstrip dispersion compensation

From (3), the group delay of the fiber can be written as:

$$ \tau_{fiber}(f) = \frac{DL^2}{c} \cdot f, $$

where we verify that positive group delays are induced for positive frequencies, for standard single mode fiber (SSMF). The group delay of a microstrip (MS) line can be described by equation (6) [8]:

$$ \tau_{ms} = -\frac{L}{c} \left( \frac{\varepsilon}{\varepsilon_{eff}} + f \frac{\varepsilon}{\varepsilon_{eff}} \right), $$

Where $\varepsilon_{eff}$ is the effective permittivity of the medium.

Notice that $\tau_{ms}$ is negative, since the permittivity of the line increases with the frequency. If the substrate and the dimensions of the MS are optimized, $\tau_{ms}$ can be approximated to $-\tau_{fiber}$ in a given frequency band. Therefore the cancellation of the fiber chromatic dispersion can be achieved in the electrical domain using a simple MS line after direct detection.

In this work a complete model that combines the amplitude limitations due to the skin effect and the dispersive effects was considered. The optimized MS line utilizes a substrate
with a permittivity of 10.2; the line and substrate thickness are 17\( \mu \)m and 1270\( \mu \)m, respectively, and the line impedance is 50 ohm. We found an ideal MS length of approximately 1.16 mm per kilometer of SSMF. In Fig. 3 we present the group delay of a MS line with 29 cm and SSMF fiber with 250km. The group delay of the microstrip was inverted for easier comparison.

A good match of the group delays is verified from low frequencies up to 10 GHz; in this range the difference between the MS line group delay and the inverted fiber group delay (deviation) is under 15 ps. For frequencies above 10 GHz the field lines are more concentrated in the substrate (and not in the air), resulting in a non-ideality in the line dispersion.

In Fig. 3 we present the group delay of a MS line with 29 cm and SSMF fiber with 250km. The group delay of the microstrip was inverted for easier comparison.

Fig. 3. Comparison of the group delay of 250km of SSMF fiber and 29mm of the described microstrip line.

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In Fig. 4 the EOP measured after transmission over dispersive fiber and several EDC schemes. Ideal EDC is compared to microstrip compensation with optimized length for each distance. Ideal EDC achieves a maximum distance of 700 km for an EOP of 5 dB (maximum allowed EOP in this work); due to the unideal amplitude and phase transfer function, a lower maximum distance, 420 km, is allowed by ideal length microstrip. Nevertheless, this distance represents a substantial improvement compared to the uncompensated scheme (maximum distance of 160 km). Additionally, a scheme appropriate for reconfigurable networks, consisting of a bank of microstrip lines\(^6\) is tested. Considering a first branch without EDC, a second with 34 cm of microstrip and a third with 50 cm of microstrip, transmission over 420 km is allowed, allowing simple and low cost adaptive dispersion compensation over a wide range.

C. Butterworth filtering dispersion mitigation

In previous work\(^6\) low pass Butterworth filters were studied as dispersion electrical equalizers for systems employing optical SSB signals. The dispersion compensation effect of a Butterworth filter is due to its non linear phase response, which originates a group delay similar to the ideal EDC group delay, within a frequency range. The low-pass Butterworth filter group delay is described by\(^9\):

\[
\tau_B(f) = \frac{1}{2\pi f_c} \cdot \frac{1}{1 + (f/f_c)^2} \sum_{i=1}^{n} \sin\left(\frac{\pi}{2n(2k-1)} \right)
\]

where \(f\) is the frequency, \(f_c\) is the 3 dB cutoff frequency, and \(n\) is the filter order. In Fig. 5 the group delay of a 7th order Butterworth filter with -3 dB bandwidth of 5.5 GHz is compared to that of the ideal EDC for 125 km\(^6\). The group delay of the Butterworth filter with an additional delay of 60 ps is also depicted for comparison; the range below the normalized frequency presents a perceptible slope similarity to the ideal EDC.

In Fig. 6, the EOP of the Butterworth filtered signal is presented for different fiber distances and compared with uncompensated oSSB and with oSSB employing ideal EDC optimized for 125 km.

Fig. 4. EOP for ideal EDC and dispersion compensation with microstrip lines, for different dispersive fiber lengths.

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Fig. 5. Group delay comparison for ideal EDC and Butterworth filter.

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Fig. 6. EOP for oSSB systems using Butterworth filtering, and employing ideal EDC configurations.
The use of the Butterworth filter introduces a back to back penalty due to the distortive filter transfer function. As the fiber length increases the EOP is less penalized than the uncompensated signal. An increase of 100 km in the maximum allowed transmission distance is obtained, comparing to the uncompensated signal. Similar result is obtained by the ideal EDC for 125 km.

Butterworth filtering proved effectiveness as a dispersive mitigation technique; furthermore, it is simple, passive, and a commercially available solution.

D. Transversal electrical adaptive filter

Transversal filters have proven effectiveness to mitigate the effects of CD in oSSB systems[10]. In this section we analyze the applicability of a transversal filter to enhance the performance of the previously presented oSSB dispersion compensators.

A transversal filter with 9 taps and 50 ps tap delay is employed. The adaptive algorithm optimizes the filter coefficients in an iterative procedure by measuring the signal eye opening and changing the filter coefficients to increase this value. A simplex[11] optimization algorithm is used, because it is a simple and robust method suitable to be implemented in a low cost peripheral interface controller (PIC)[12].

Hybrid EDC schemes are investigated in this section: combination of 29 cm microstrip and the adaptive filter; and Butterworth filter followed by the adaptive filter. The performance of these configurations is presented in Fig. 7 and compared to schemes employing only one EDC method.

The use of the hybrid solution demonstrates clear reconfigurable dispersion mitigation effectiveness using implementable methods. High improvements result from cascading adaptive filters with other steady EDC methods. This solution enables maximum transmission distances similar to that obtained with ideal EDC. The ideal EDC cannot compensate undesired terms introduced by the square-law detection and non-ideal oSSB modulation. Comparing to the ideal EDC, the hybrid solutions allow improved results because the adaptive filter works on the optimization of the eye opening, being able to increase it further when a previous EDC is used.

V. CONCLUSIONS

Different approaches to perform electrical chromatic dispersion compensation in an optical SSB system were studied in this work, and special attention was provided to feasible solutions.

By using optical SSB modulation with an optimized length microstrip line as equalizer in the receiver, it is possible to transmit a 10 Gbit/s signal through more than 420 km of dispersive fiber with an EOP lower than 5 dB, without resort to any optical compensation scheme. Similar distance has been achieved by a reconfigurable bank of 2 microstrip lines.

Butterworth filtering was considered as an EDC method: 260 km of transmission distance have been covered, which represents an improvement of 100 km, when compared to the uncompensated scheme.

A hybrid configuration, consisting on a fixed microstrip line or a Butterworth filter followed by an adaptive transversal filter demonstrated promising results: maximum transmission distances higher than 600 km are achieved with this stand alone solution.

REFERENCES


Fig. 7. EOP for systems employing different hybrid EDC configurations.